Discussion on Ten Major Environmental Concerns in China's In-Situ Uranium Leaching

Authors: Lian Guoxi, Li Mengjiao, Sun Juan, Yang Bing, An Yifu, Yunxuan Liao, Eileen Chang, Shang Zhaorong, Lian Guoxi

Date: 2024-05-23T00:00:00+00:00

Abstract

In-situ leaching uranium mining is the primary technology for natural uranium production in China, and environmental protection issues associated with its construction, operation, and decommissioning have received widespread attention. This paper introduces the generation of "three wastes" from in-situ leaching uranium mining, proposes ten key issues of concern including determination of production-to-injection ratio, treatment and disposal of drilling mud, monitoring well layout, determination of groundwater background values, identification of monitoring well data anomalies, process wastewater treatment, evaporation pond operation and management, determination of groundwater remediation target values, groundwater remediation, and waste minimization, discusses the current status of technology and management, identifies the main tasks and research directions in the field of environmental protection for in-situ leaching uranium mining in the future, with the aim of providing references for the sustainable development of in-situ leaching uranium mining in China.

Full Text

Discussion on Ten Key Environmental Protection Issues in China's In-situ Leaching Uranium Mining

LIANG Guoxi[1,2], **SUN Juan**[3], **LI Mengjiao**[3], **AN Yifu**[3], **YANG Bing**[1], **LIAO Yunxuan**[1], **SHANG Zhaorong**[1]

[1] Nuclear and Radiation Safety Center, Ministry of Ecology and Environment, Beijing 100082, China
[2] School of Environment, Beijing Normal University, Beijing 100875, China

[3] The Fourth Research and Design Engineering Corporation of CNNC, Shijiazhuang 050021, China

Abstract

In-situ leaching is the primary technology for natural uranium production in China, and its environmental protection issues during construction, operation, and decommissioning have attracted widespread attention. This paper introduces the generation of "three wastes" from in-situ leaching uranium mining, proposes ten key environmental concerns including bleed ratio determination, drilling mud treatment and disposal, monitoring well layout, groundwater baseline determination, monitoring well data anomaly identification, process wastewater treatment, evaporation pond operation and management, groundwater restoration target value determination, groundwater remediation, and waste minimization. The current state of technology and management is discussed, and the main tasks and research directions for future environmental protection in China's in-situ leaching uranium mining are identified, aiming to provide references for the sustainable development of this industry.

Keywords: In-situ leaching uranium; Groundwater; Environmental protection; Pollution prevention and control

Uranium is a crucial strategic mineral resource, with global demand projected to reach 80,000–148,500 tons per year by 2030. Uranium extraction primarily occurs through three methods: underground mining, open-pit mining, and in-situ leaching. In-situ leaching has seen its share of world natural uranium production increase significantly from 16% in 2000 to over 60% in 2021, owing to advantages such as lower capital investment, shorter construction periods, reduced operating costs, and relatively minimal environmental impact. The process involves injecting lixiviant through injection wells into permeable uranium ore zones, where it migrates and reacts with uranium minerals under natural conditions to produce uranium-bearing solutions that are then collected through production wells. Based on the lixiviant type, methods are categorized as acid (typically using H_2SO_4 and H_2O_2), neutral (CO_2+O_2), or alkaline (Na_2CO_3).

Environmental protection issues in in-situ leaching uranium production have garnered extensive attention. Drawing upon years of practical experience in environmental protection for in-situ leaching uranium mining and based on domestic and international production, management, and research status, this paper examines ten critical environmental protection issues in in-situ leaching uranium mining and outlines future research directions for environmental protection technologies in this field.

1. Overview of In-situ Leaching Uranium Production and Waste Management

China's in-situ leaching uranium mining began in the 1980s, with the successful trial at the Yunnan 381 deposit in 1984 marking the initial mastery of the technology, followed by industrial application in the Yili Basin in 2000. Since then, multiple in-situ leaching uranium mines have been constructed, including acid leaching facilities such as Xinjiang 737 Plant, 739 Plant, and Inner Mongolia Bayan Wula, as well as neutral leaching facilities including Xinjiang 735 Plant, 738 Plant, Tongliao Qian II Block, and Qian IV Block. By 2021, in-situ leaching uranium production capacity accounted for over 80% of China's total natural uranium output, establishing it as the mainstream uranium extraction technology.

Production facilities primarily consist of wellfields, hydrometallurgical plants, and waste treatment installations. Wellfields comprise production wells (including production and injection wells) and monitoring wells, serving as the infrastructure for uranium leaching and extraction within the deposit. Hydrometallurgical plants include leachate filtration units, adsorption facilities, elution facilities, and precipitation/pressure filtration units for uranium extraction from leachate. Waste treatment facilities encompass wastewater treatment plants and evaporation ponds. The typical production process flows as: lixiviant injection → orebody leaching → leachate extraction → filtration → adsorption → elution → precipitation → pressure filtration and washing → natural uranium product.

In-situ leaching generates radioactive waste gas, wastewater, and solid waste. Radioactive waste gas consists mainly of radon and its progeny, primarily produced at wellfield collection ponds (tanks), hydrometallurgical workshops, and evaporation ponds, and is typically discharged through mechanical or natural ventilation for atmospheric dilution. Radioactive wastewater includes adsorption tailings, transformation tailings, product washing water, and well-washing wastewater, with most being sent to evaporation ponds for natural evaporation after partial recycling. Solid waste comprises drilling mud, leachate filtration residues, spent resin, and contaminated pipelines and equipment. Drilling mud is mostly buried on-site, leachate filtration residues are temporarily stored in evaporation ponds, and spent resin and contaminated equipment are stored in solid waste temporary storage facilities. Due to substantial chemical reagent injection, groundwater restoration is required after production cessation, and production facilities must be decommissioned due to radioactive contamination. Overall, the "three wastes" from in-situ leaching have been properly treated and disposed of, though environmental protection standards in the industry need further improvement amid scaled development and increasingly stringent environmental requirements.

2. Ten Key Environmental Protection Issues in In-situ Leaching Uranium Mining

Based on the entire lifecycle of in-situ leaching uranium mining from design through construction, operation, and decommissioning, this section examines ten critical environmental protection issues (Figure 1 [Figure 1: see original paper]). Design should focus on bleed ratio determination; construction should address drilling mud treatment and disposal, monitoring well layout, and groundwater baseline determination; operation should concentrate on monitoring well data anomaly identification, process wastewater treatment, and evaporation pond operation and management; and decommissioning should prioritize groundwater restoration target value determination, groundwater remediation, and waste minimization.

2.1 Determination of Bleed Ratio

The bleed ratio refers to the percentage by which production well flow exceeds injection well flow. Maintaining a bleed ratio in in-situ leaching operations creates a localized groundwater depression cone that controls the leaching zone, prevents leachate dispersion, and protects groundwater environmental safety. While a larger bleed ratio creates a more significant depression cone and smaller leaching range, it also generates more radioactive wastewater, requiring larger evaporation ponds, occupying more land resources, and releasing more radon gas. Therefore, the bleed ratio should be minimized while ensuring groundwater environmental safety.

Foreign in-situ leaching mines typically control bleed ratios between 0.5% and 2%, averaging approximately 1%. For example, Australia's Honeymoon mine operates at 0.5%–2%, Beverley mine at 0.5%, and U.S. Smith Ranch and Crow Butte mines at 0.5%–1.5% and 0.5%–1.0%, respectively. Chinese standards for bleed ratio determination include the *Code for Design of Uranium Mining and Metallurgy Engineering* (GB50521-2009), which specifies in Section 5.10.3 that "production flow should exceed injection flow by 0.3%–1.0%," and the *Regulations for Radiation Protection and Environmental Protection in Uranium Mining and Metallurgy* (GB23727-2020), which states in Section 6.2.4.2 that "in-situ leaching mine design should reasonably determine the ratio of production flow exceeding injection flow based on hydrogeological characteristics, with boundary production-injection units requiring at least 0.5% excess production flow." China's operating in-situ leaching uranium mines maintain bleed ratios of 0.3%–1.0% (Table 1), meeting national standards and aligning with international levels. No significant monitoring well anomalies have been observed at these bleed ratio levels.

The bleed ratio aims to control the in-situ leaching zone, which is also influenced by hydrogeological conditions, wellfield layout, and production-injection operations. Research indicates that leaching zone changes are not sensitive to small variations in bleed ratio. Studies on a typical in-situ leaching block show that increasing the bleed ratio from 0.1% to 3% increases downstream uranium migration distance from 75 m to 94 m—only a 19 m increase. The leaching zone is closely related to hydrogeological conditions such as permeability coefficient and hydraulic gradient. For low-permeability sandstone, the leaching zone is even less affected by bleed ratio due to slower diffusion rates, allowing for appropriate bleed ratio reduction in areas with favorable hydrogeological conditions. Additionally, wellfield flow regulation and non-uniform injection-production technology can control the leaching zone. Non-uniform injection-production technology, which increases boundary production well flow and reduces peripheral injection well flow, effectively controls the leaching zone, as does rational injection flow distribution for nuclide migration control.

To further optimize the bleed ratio, research should focus on: (1) the synergistic relationship among leaching zone, bleed ratio, and hydrogeological conditions; (2) field verification studies on the relationship between bleed ratio and leaching zone, as previous research has relied primarily on numerical simulation; and (3) wellfield precision regulation and real-time groundwater monitoring technologies.

2.2 Treatment and Disposal of Drilling Mud

Drilling mud is a water-based colloid generated during in-situ leaching well drilling and development, classified as solid waste. Since drilling penetrates ore-bearing horizons, the mud inevitably contains radioactive materials at levels ranging from tens to hundreds of Bq/kg, rarely exceeding 1 kBq/kg, allowing treatment as non-radioactive solid waste in most cases.

Drilling mud is typically weakly alkaline, composed mainly of silicon dioxide, aluminum oxide, calcium oxide, and iron oxide, with low heavy metal content and relatively simple composition. However, it features high density, high sand content, high viscosity, and low water content. Direct discharge without treatment may affect soil structure and harm plant growth. Treatment and disposal methods vary depending on the drilled formation horizon, with "mud non-settlement" technology representing an advanced industry approach. Ore horizon drilling mud is typically reused for well cementing using cementitious glassy hydraulic materials. Non-ore horizon drilling mud is separated by vibrating screens and hydrocyclones into high-solid and low-solid fractions. High-solid mud undergoes surface solidification and burial, commonly using polymeric flocculants, polyaluminum chloride, and ferrous sulfate as flocculants, with cement as the solidifying agent—significantly reducing surveillance periods and improving disposal efficiency compared to direct burial. Low-solid drilling fluid from non-ore horizons is recycled. Current drilling mud treatment technology is mature, achieving 100% treatment rates with approximately 60% recycled, 20%–25% solidified and buried with soil cover and vegetation restoration, and 15%–20% used for well cementing.

Key considerations include: (1) Drilling mud radioactivity levels depend on multiple factors, and for newly developed mining blocks, sampling and monitoring should be conducted to determine radioactivity levels and guide appropriate classification and treatment, with radioactive mud disposed of as radioactive solid waste; and (2) Drilling mud from in-situ leaching block development should be buried as centrally as possible with proper surface soil cover and vegetation restoration.

2.3 Monitoring Well Layout

Monitoring wells are specialized facilities for monitoring groundwater environmental quality and dynamic changes in groundwater composition, representing critical infrastructure for groundwater environmental protection. To directly reflect water quality changes, monitoring wells must be installed in aquifers above, within, and below the ore zone. The *Regulations for Radiation Protection and Environmental Protection in Uranium Mining and Metallurgy* (GB 23727-2020) specifies that "for ore-bearing aquifers, monitoring wells should be arranged 50–150 m beyond the block boundary wells, with downstream monitoring wells extending at least 300 m. Corresponding monitoring wells should be installed in the upper aquifer, with lower aquifer wells arranged as appropriate based on regional geology and hydrogeology." The *Code for Design of Uranium Mining and Metallurgy Engineering* (GB 50521-2009) states that "the number of monitoring wells should be 2%–10% of production wells, with no fewer than 2 monitoring wells in the downstream direction, and corresponding wells in upper and lower aquifers within the wellfield."

While national standards provide general requirements, they do not specify layout methods such as placement points or spacing distances. Monitoring well locations are typically determined using numerical simulation methods based on hydrogeological conditions, wellfield layout, and injection-production flow parameters to model contaminant migration distances. For well spacing, the U.S. NRC specifies that the angle between two monitoring wells and a production well should not exceed 75°. For overlying and underlying aquifer monitoring wells, the network density is one well per 3–5 acres. Common groundwater samplers include submersible pumps, stratified samplers, and fixed-depth samplers. Conventional practice requires pumping three times the wellbore volume before sampling after water level recovery. However, research shows that pumping three well volumes may cause leachate overflow due to high hydraulic gradients from injection wells, leading to significant increases in monitoring parameters.

Although national standards provide general monitoring well requirements, more specific specifications for layout and sampling are needed. Future work should strengthen: (1) research on monitoring well layout methods, such as for in-situ leaching condition tests with only a few injection-production units where layout approaches require study; (2) research on monitoring well spacing based on leachate overflow scenarios; and (3) research on sampling representativeness to develop monitoring well sampling technical specifications.

2.4 Determination of Groundwater Baseline Values

Groundwater baseline values represent the original regional groundwater quality level before in-situ leaching production, serving as a critical basis for evaluating production impacts and determining groundwater restoration targets. Hydrological borehole water quality data from uranium geological exploration can provide preliminary baseline values, but limited borehole numbers and uneven distribution result in poor representativeness, and some uranium deposits exhibit significant baseline variations due to complex mineralization. Therefore, to scientifically determine baseline values, groundwater monitoring should be conducted after block development drilling is completed but before production begins, serving as the primary basis for baseline determination.

Groundwater baseline values include block baselines and monitoring well baselines. Block baselines derive from representative production well water quality data and are crucial for determining block groundwater restoration targets. Monitoring well baselines derive from monitoring well water quality data and serve as important references for leaching zone dispersion during production.

U.S. NRC research reports indicate that baselines should be determined on a block basis, requiring at least four sampling events with appropriate time intervals to reflect temporal groundwater quality variations. In-situ leaching operations should sample all perimeter monitoring wells, upper and/or lower aquifer monitoring wells, and several production wells, with production wells used for baseline determination generally numbering no fewer than six, at a sampling density of one production well per 4,000–16,000 m^2.

Groundwater baseline monitoring factors are closely related to ore composition and production processes. U.S. regulations specify that baseline monitoring should include pH, uranium, ^{226}Ra, arsenic, barium, boron, cadmium, calcium, ammonia nitrogen, chloride, chromium, copper, fluoride, iron, lead, magnesium, manganese, mercury, molybdenum, nickel, nitrate, nitrite, potassium, selenium, sodium, sulfate, TDS, total carbonate, uranium, vanadium, zinc, and others. Radioactive indicators include uranium and ^{226}Ra, while non-radioactive factors include trace and minor elements, conventional anion/cation components, and physical indicators. China has recently strengthened requirements for in-situ leaching groundwater baseline determination. For a particular mine, monitoring was conducted in initial mining blocks with all production wells tested for pH, uranium, bicarbonate, sulfate, and chloride, and three production wells per block tested for ^{226}Ra, ^{210}Po, and ^{210}Pb, along with comprehensive non-radioactive water quality analysis. This effort accumulated substantial data for baseline research but involved heavy workload, high investment, and long cycles.

Future research on in-situ leaching groundwater baseline determination should: (1) investigate the representativeness of production well sampling density to optimize sampling quantity; (2) examine baseline sampling frequency and time intervals; and (3) explore whether local groundwater baseline values can be determined comprehensively from several adjacent monitoring wells, considering that the hydraulic cone from bleed ratio can cause peripheral groundwater intrusion and water quality fluctuations.

2.5 Abnormal Data Determination for Monitoring Wells

In-situ leaching inevitably causes leachate dispersion, leading to monitoring well groundwater indicator anomalies. Seasonal variations, sampling operations, and analytical errors also cause monitoring result deviations, making the definition of monitoring well data anomalies critical for determining normal production status. The *Regulations for Radiation Environmental Monitoring of In-situ Leaching Uranium Mines* (Q/CNNC JB 12-2014) specifies that indicator parameters exceeding baseline values by 20% during production indicate leachate deviation. However, practice shows that if selected indicator parameters have low baseline values, frequent alarms exceeding 20% occur. Leachate deviation indicators should be significant parameters of the leaching process that do not participate in aquifer geochemical reactions and are easily analyzed. The U.S. NRC recommends establishing at least three deviation indicators, with deviation confirmed when two or more factors exceed control limits in monitoring wells. The *Regulations for Radiation Environmental Monitoring of Uranium Mining and Metallurgy* (GB 23726-2009) specifies groundwater monitoring parameters as U-natural, ^{226}Ra, ^{210}Po, and ^{210}Pb at a frequency of once every six months, which is insufficient for indicating leachate deviation. Control limits must be lower than the minimum concentration of the factor in leachate but higher than baseline values. Two methods are commonly used: (1) percentage above baseline values, and (2) statistical methods, typically setting control limits at five times the standard deviation of concentration averages, with larger standard deviations applicable in areas with good water quality. Since uranium and cations are susceptible to geochemical effects such as adsorption and precipitation, they are not ideal indicators; common alternatives include pH, sulfate, TDS, chloride, and alkalinity.

The greatest environmental risk in in-situ leaching uranium mining is groundwater pollution from leachate dispersion. China has not yet established standards for deviation indicator selection and deviation criteria. Targeted research should be conducted on monitoring well indicator selection and reasonable data deviation determination methods to establish indicators and monitoring frequencies for different in-situ leaching production processes.

2.6 Process Wastewater Treatment

Wastewater from China's in-situ leaching production includes well-washing water, adsorption tailings, transformation waste liquid, precipitation mother liquor, reverse osmosis concentrate, and product washing water, with uranium concentrations generally at 1–3 mg/L and ^{226}Ra activity concentrations at 1–10 Bq/L. Well-washing water is mostly recycled to production wells after solid-liquid separation, while other wastewater is sent to evaporation ponds for natural evaporation after recycling.

U.S. in-situ leaching wastewater treatment methods include evaporation ponds, land application, deep well injection, and discharge. Evaporation ponds are commonly used, such as at the natural evaporation pond for uranium mining in Montrose County, Colorado. Land application involves using treated water for surface spraying and vegetation irrigation, requiring minimized uranium and radium content to avoid radioactive contamination of surface soil and plants, with regular soil and plant monitoring necessary. Deep well injection involves injecting waste liquid into and sealing it within deep confined aquifers 500–3,500 m below the surface, where water quality is typically poor (e.g., high salinity or total dissolved solids) and non-functional, serving as a method for treating specific wastewaters, as employed at the U.S. Smith Ranch in-situ leaching uranium mine for reverse osmosis concentrate.

China has recently researched electrodialysis, reverse osmosis, and MVR technologies for treating in-situ leaching process wastewater, which can separate wastewater into concentrate and freshwater with quality meeting or exceeding local groundwater baseline levels. However, these technologies have not been applied due to cost issues and lack of freshwater discharge options.

In-situ leaching process wastewater solutions should focus on source control and developing new treatment technologies: (1) optimizing bleed ratio to reduce wastewater generation, particularly for neutral in-situ leaching mines with favorable hydrogeological conditions; (2) improving wastewater treatment efficiency by developing low-level wastewater purification technologies to further reduce high-concentration waste production; and (3) expanding freshwater discharge options, verifying the technical and practical feasibility of using treated water for grassland irrigation or groundwater recharge.

2.7 Operation and Management of In-situ Leaching Evaporation Ponds

China's leachable uranium resources are primarily located in arid northern regions such as Xinjiang and Inner Mongolia, where no receiving water bodies exist, necessitating natural evaporation pond construction for wastewater treatment. Due to simple engineering, easy operation, energy efficiency, and high decontamination factors, natural evaporation ponds are widely used for volume reduction in seawater salt production, industrial wastewater, and hazardous chemical waste treatment. They are extensively applied for low-level radioactive liquid waste treatment at facilities such as the Rocky Flats Plant in Denver, Colorado (the largest U.S. nuclear weapons materials metallurgy and processing base), the 183-H evaporation pond at the Hanford Site, the Lucas Heights evaporation pond in Australia, and natural evaporation ponds at Korean uranium conversion plants. In the in-situ leaching uranium mining sector, multiple uranium mining and metallurgical facilities in the U.S. have constructed natural evaporation ponds.

In-situ leaching evaporation ponds typically feature trapezoidal cross-sections with external slopes and fences, perimeter embankments to prevent surface rainwater and reduce windblown sand ingress. Pond bottoms and slopes are lined with bentonite mats and HDPE geomembranes for seepage prevention, with 0.3–0.5 m thick backfill soil covering the geomembrane to prevent aging from sunlight exposure, frost damage, and mechanical damage, while pond walls are protected with clay brick masonry. Advanced distributed optical fiber leak detection systems are installed for online leakage monitoring, with groundwater monitoring wells surrounding the perimeter.

Operational issues include large land area occupation, birds mistaking evaporation ponds for natural wetlands and affecting ecology, occasional odor nuisance from discharging small amounts of domestic or other wastewater during management, and disposal of radioactive solid waste such as spent resin and leachate residues in evaporation ponds. To improve efficiency, researchers have developed wind-enhanced curtain evaporation, pond spraying, and solar heating technologies, with wind-enhanced devices improving evaporation rates by over 20 times compared to natural evaporation. Alternative technologies such as MVR forced evaporation have also been investigated.

Future work on in-situ leaching evaporation ponds should: (1) advance engineering demonstrations of developed technologies such as solar low-temperature evaporation and curtain evaporation; (2) promote alternative technologies like MVR forced evaporation; (3) research freshwater discharge options such as grassland irrigation or groundwater recharge feasibility; (4) optimize protective layer materials for pond liners, as current clay layers generate substantial radioactive solid waste; and (5) strengthen evaporation pond operation management to prevent entry of wastes other than wastewater.

2.8 Determination of Groundwater Restoration Target Values

Determining groundwater restoration target values is fundamental to in-situ leaching uranium mining groundwater remediation. Scientifically reasonable target values are crucial for sustainable development. The U.S. has the most stringent requirements, with the NRC's 2003 *Standard Review Plan for In Situ Leach Uranium Extraction License Applications* establishing three-tiered restoration standards: (a) primary standards—meeting pre-mining baseline levels; (b) secondary standards—meeting water quality standards corresponding to pre-mining water use (e.g., drinking, livestock, industrial), applicable to specific components that cannot be restored to baseline; and (c) alternative standards—allowing components to exceed secondary standards based on technical and economic considerations, typically for low-health-risk parameters such as TDS, sulfate, chloride, and iron, requiring approval from state environmental management departments.

For non-radioactive groundwater pollution control, China issued the *Techni-*

cal Guidelines for Groundwater Remediation and Risk Control of Contaminated Sites (HJ 25.6-2019), establishing groundwater restoration target values and risk control target values. For drinking water source protection areas and recharge zones, Class III limits from the *Groundwater Quality Standards* (GB/T 14848-2017) serve as restoration targets, with risk control values calculated for unlisted pollutants based on drinking water exposure pathways. For areas with industrial or agricultural water use functions, Class IV limits establish restoration targets, with risk control values calculated via risk assessment for unlisted pollutants. For areas without such functions, risk control values are calculated through risk assessment. When restoration targets are lower than groundwater baseline values, baseline values are adopted as targets. Additionally, groundwater risk control target values should be established when technical and economic assessments demonstrate that restoration targets cannot be achieved. Thus, China's contaminated site groundwater restoration targets are based primarily on groundwater use pathways, with the highest requirement being Class III water quality standards, not necessarily requiring restoration to baseline levels.

China has not yet established methods for determining in-situ leaching uranium mining groundwater restoration target values. Research should focus on: (1) groundwater function zoning and potential use pathways, as some in-situ leaching mines have high mineralization and baseline levels in ore-bearing aquifers lacking industrial or agricultural use functions, requiring realistic restoration targets; (2) developing human exposure assessment models and parameters based on radioactive and non-radioactive pollutants to calculate human health risks across various exposure pathways; and (3) establishing cost-benefit analysis models based on feasible remediation technologies to study risk control approaches for pollutants that cannot be remediated to target levels.

2.9 Groundwater Remediation

Groundwater remediation technologies are categorized as active or passive. Active remediation includes pump-and-treat, chemical reduction, and bioreduction; passive remediation primarily involves monitored natural attenuation. Pump-and-treat extracts contaminated groundwater from ore-bearing aquifers to the surface for treatment before discharge or reinjection, achieving contaminant removal through multiple pore volumes of extraction. This method offers rapid remediation, good initial effectiveness, and mature technology but suffers from high costs, tailing and rebound effects, and radioactive solid waste generation from wastewater treatment. Chemical reduction injects reducing agents into ore-bearing aquifers to restore pre-mining reducing conditions and immobilize contaminants, commonly using Na_2S, Na_2SO_3, H_2S, and H_2. This method provides relatively fast, mature remediation but at high cost with potential secondary pollution. Bioremediation injects microorganisms or carbon sources to promote contaminant reduction or immobilization through microbial reduction, mineralization, adsorption, and accumulation, offering low cost and minimal secondary pollution but long remediation cycles, slow onset, and reoxidation/rebound risks. Monitored natural attenuation implements planned groundwater monitoring to rely on natural purification processes (including dilution, diffusion, adsorption, complexation/precipitation, and bioreduction) for gradual contaminant concentration reduction, featuring low cost and no secondary pollution but long remediation periods and inapplicability to highly contaminated areas.

Pump-and-treat, chemical reduction, and bioremediation are often combined as mature in-situ leaching uranium mining groundwater remediation methods, with practical applications at U.S. mines including Smith Ranch-Highland and Crow Butte. Pump-and-treat requires extracting multiple pore volumes; statistics from 25 remediated blocks in Texas show extraction volumes ranging from 2.4 to 25.7 pore volumes, with most mines achieving significant contaminant concentration reductions post-remediation, including 32% of blocks where uranium fell below baseline levels. Bioremediation trials at the Smith Ranch-Highland B ore body using Na_2S chemical reduction followed by methanol and molasses stimulation showed rapid selenium reduction and initial uranium increase followed by significant decrease. Downstream ore-bearing aquifers at uranium mines generally possess good reducing capacity, with residual contaminants naturally attenuating post-mining through physical, chemical, and biological processes. Kazakhstan's Irkol deposit and Uzbekistan's Bukinai deposit showed reductions in pH, uranium, radium, iron, aluminum, sulfate, and nitrate after over a decade of natural attenuation.

Although in-situ leaching groundwater remediation has practical experience, remediation effectiveness is influenced by various factors including baseline levels, geochemical characteristics, aquifer thickness and continuity, porosity, and permeability, giving groundwater remediation a "one-mine-one-policy" characteristic. Future research should: (1) initiate groundwater remediation technology route exploration early, studying remediation processes during condition tests or pilot tests; (2) investigate the applicability of various approaches based on active and passive remediation, applying monitored natural attenuation in remote areas without groundwater use requirements; (3) develop remediation chemical reagents and biological agents to reduce secondary pollution; (4) research appropriate engineering technologies to improve remediation efficiency and stability; and (5) conduct groundwater remediation engineering verification at typical uranium mines following a "mine-while-remediate" principle.

2.10 Waste Minimization

Post-mining decommissioning requires remediation of surface facilities and contaminated sites, including proper disposal of radioactive solid waste such as leachate residues, wastewater treatment sludge, evaporation pond contaminated soil, and contaminated structures, pipelines, and equipment. This requires construction of disposal facilities and may result in limited-release sites or even long-term surveillance.

As an advanced and environmentally friendly uranium extraction process, in-situ leaching uranium mining should minimize radioactive waste generation to better demonstrate environmental friendliness. Waste minimization efforts should: (1) incorporate waste minimization concepts during design by selecting easily decontaminable materials for structures and implementing strict management during production to reduce contaminated site generation, such as preventing hydrometallurgical plants from becoming radioactive contaminated sites; (2) conduct in-depth research on contaminated soil remediation technology, as in-situ leaching radioactive contaminated soil primarily results from wastewater leaching with single contamination pathways and relatively simple remediation, enabling maximum contaminated soil volume reduction; and (3) achieve centralized disposal to the greatest extent possible, with centralized waste disposal site planning and construction being essential for China's in-situ leaching uranium mining distribution in Xinjiang and Inner Mongolia.

Conclusion

1) Based on practical experience from China's in-situ leaching uranium mining projects and drawing upon domestic and international research progress, this paper identifies ten key environmental protection issues across the entire lifecycle of in-situ leaching uranium mining from design, construction, operation, and decommissioning: bleed ratio control, drilling mud treatment and disposal, monitoring well layout, groundwater baseline determination, monitoring well data anomaly identification, process wastewater treatment, evaporation pond operation and management, groundwater restoration target value determination, groundwater remediation, and waste minimization.

2) As an advanced and environmentally friendly uranium extraction method, in-situ leaching uranium mining has matured technologically after decades of development. With increasingly stringent national environmental protection requirements, higher demands are placed on environmental protection in this sector. Future efforts should continue strengthening environmental protection technology research and management levels to promote high-quality development of in-situ leaching uranium mining.

References

[1] Su Xuebin, Du Zhiming. Current status and prospects of in-situ leaching uranium mining technology development in China[J]. China Mining Magazine, 2012, 21(9): 79-83.
[2] Sun Zhanxue, Ma Wenjie, Liu Yajie, et al. Research progress on groundwater environment restoration at in-situ leaching uranium mines[J]. Earth Science Frontiers, 2021, 28(5): 208-214.
[3] Ministry of Ecology and Environment, State Administration for Market Regulation. Regulations for radiation protection and radiation environmental

protection in uranium mining and metallurgy: GB 23727-2020[S]. Beijing: Standards Press of China, 2020.

[4] Su Xuebin, Chang Jingtao. Proceedings of the 60th Anniversary Scientific and Technological Achievements Exchange Conference of China's Uranium Mining and Metallurgy[C]. Shijiazhuang, 2018.

[5] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Ministry of Housing and Urban-Rural Development of the People's Republic of China. Code for design of uranium mining and metallurgy engineering: GB50521-2009[S]. Beijing: China Planning Press, 2009.

[6] Lian Guoxi, Li Mengjiao, Tang Qingsi, et al. Study on the relationship between bleed ratio and groundwater environmental impact at an in-situ leaching wellfield[J]. Uranium Mining and Metallurgy, 2017, 36(2):

[7] Cao Yingxue. Practice and exploration of different bleed ratio controls on groundwater environment in in-situ leaching uranium mining[J]. Uranium Mining and Metallurgy, 2017, 36(2): 134-143.

[8] Ji Hongbin, Huang Qunying, Zhou Yipeng, et al. Influence of injection-production flow distribution and bleed ratio on leaching solution diffusion in in-situ leaching[J]. Uranium Mining and Metallurgy, 2017, 36(3): 172-181.

[9] Xu Qiang. Study on the influence of bleed ratio on leaching range in in-situ leaching uranium mines[J]. Uranium Mining and Metallurgy, 2017, 36(Supplement):93-97.

[10] Zhang Yong, Ma Lianchun, Zhang Bo, et al. Discussion on the impact of leaching process on groundwater environment in low-permeability uranium deposits[J]. Uranium Mining and Metallurgy, 2017, 36(Supplement): 75-86.

[11] Li Mengjiao, Lian Guoxi, Cao Fengbo, et al. Application of non-uniform injection-production technology in groundwater environmental protection for in-situ leaching[J]. Uranium Mining and Metallurgy, 2017, 36(Supplement): 98-104.

[12] Gao Xianfeng, Li Xilong, Zhang Yong. Study on harmless treatment process of waste drilling fluid from in-situ leaching uranium mining[J]. Uranium Mining and Metallurgy, 2017, 36(4): 273-283.

[13] Liang Qishen, Hu Baishi, Qin Hao. Process method for purification and treatment of waste drilling mud from in-situ leaching boreholes[J]. Uranium Mining and Metallurgy, 2016, 35(1): 16-20.

[14] Xu Jianjun, Yuan Yuan, Xia Xu. China Nuclear Science and Technology Progress Report (Volume 6)[C]. Baotou, 2019.

[15] Wang Haifeng, Li Jiandong, Liu Zhengbang, et al. Research progress on drilling construction and well completion technology for in-situ leaching uranium mining in China[J]. Uranium Mining and Metallurgy, 2022, 4(13): 195-201.

[16] U.S.NRC. Standard Review Plan for In Situ Leach Uranium Extraction License Applications[R]. 2003.

[17] Wang Haifeng. Sampling method and monitoring result analysis of monitoring wells in in-situ leaching uranium mining[J]. Uranium Mining and Metallurgy, 2002, 21(2): 57-61.

[18] Wen Jili, Peng Yang, Xu Jianjun, et al. Water sampling technology for monitoring wells in in-situ leaching uranium mines[J]. Uranium Mining and Metallurgy, 2018, 37(2): 147-160.
[19] The Fourth Research and Design Engineering Corporation of CNNC, CNNC North Uranium Co., Ltd. Environmental Impact Report for Qianjiadian Qian II Block In-situ Leaching Uranium Mining. Shijiazhuang: The Fourth Research and Design Engineering Corporation of CNNC, 2013.
[20] U.S.NRC. Consideration of Geochemical Issues in Groundwater Restoration[R]. Washington DC, 2003.
Cameco. Environment Safety Crow-butte [EB/OL]. (2023.5.6)[2023.6.7]. https://www.cameco.com/businesses/uranium-operations/suspended/crow-butte/environment-safety.
[22] Zeng Zhiwei, Wang Pan, Zhan Jingming, et al. Enhanced natural evaporation of low-level radioactive wastewater in evaporation ponds using carbon fiber evaporation curtains[J]. Industrial Water Treatment, 2022, 42(2): 160-165.
[23] Li Xilong, Wang Haizhen, Yu Longfeng, et al. Research and application of wind energy enhanced evaporation device in in-situ leaching uranium mines[J]. Uranium Mining and Metallurgy, 2019, 38(2): 128-132.
[24] Wang Zhanlong, Du Juan, Li Li, et al. Study on MVR treatment technology for evaporation pond wastewater from neutral in-situ leaching uranium mines[J]. Uranium Mining and Metallurgy, 2023, 42(42): 89-100.
[25] Ministry of Ecology and Environment. Technical guidelines for groundwater remediation and risk control of contaminated sites[S]. Beijing: China Environment Publishing Group, 2019.
[26] Mudd, Gavin. Critical review of acid in situ leach uranium mining: 1. USA and Australia[J]. Environmental Geology, 2001, 41(3-4): 390-403.
[27] Mudd, Gavin. Critical review of acid in situ leach uranium mining: 2. Soviet Block and Asia[J]. Environmental Geology, 2001, 41(3-4): 404-416.
[28] Rong Yao, Rong Kexuan. Groundwater restoration technologies for foreign in-situ leaching uranium mines[J]. Uranium Mining and Metallurgy, 2021, 40(02): 158-164.
[29] Chen Yueyu, Zhang Hui, Hu Nan, et al. Research progress on groundwater restoration technology for in-situ leaching uranium mining[J]. Mining Research and Development, 2021, 41(02): 149-154.
[30] HALL S. Groundwater restoration at Uranium in-situ recovery mines, south Texas coastal plain[R]. Reston: Geological Survey, 2009.
[31] Basu A, Brown S T , Christensen J N , et al. Isotopic and Geochemical Tracers for U(VI) Reduction and U Mobility at an in Situ Recovery U Mine[J]. Environ Sci Technol, 2015, 49(10): 5939-47.
[32] Reimus P W, Dangelmayr M A, Clay J T, et al. Uranium Natural Attenuation Downgradient of an in Situ Recovery Mine Inferred from a Cross-Hole Field Test[J]. Environ Sci Technol, 2019, 53(13): 7483-7493.
[33] Saunders J A, Pivetz B E, Voorhies N, et al. Potential aquifer vulnerability in regions down-gradient from uranium in situ recovery (ISR) sites[J]. Journal of Environmental Management, 2016, 183: 67-83.
[34] IAEA. The uranium production cycle and the environment[R]. Vienna:

International Atomic Energy Agency, 2000.

Note: Figure translations are in progress. See original paper for figures.